Hysteresis and Domain Formation in a Double-Layer Quantum Hall System at total Filling Factor 2

J.G.S. Lok, A.K. Geim, B. Tieke, J.C. Maan
High Field Magnet Laboratory, Research Institute for Materials, University of Nijmegen, NL-6525 ED Nijmegen, The Netherlands

S.T. Stoddart, R.J. Hyndman, B.L. Gallagher, and M. Henini
Department of Physics, University of Nottingham, Nottingham NG7 2RD, England

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We report anomalous behavior in a double-layer two dimensional hole gas (2DHG) at even integer filling factors which includes a hysteresis in the longitudinal and Hall resistances and a very weak temperature dependence of the resistance minima. All anomalies disappear and the conventional quantum Hall effect behavior recovers when a thin metal film is placed on the top of the 2DHG. The behavior is attributed to the presence of the theoretically predicted magnetic ordering at even integer filling factors which causes the formation of macroscopic spin-charge domains.

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Double-layer spin-polarized two dimensional systems have recently been under intense scrutiny due to extraordinary magnetic properties they are expected to exhibit [1,2]. These properties arise from interlayer Coulomb and exchange interactions. Depending in a subtle way on these interactions as well as the Zeeman energy and the splitting between subbands, both ferromagnetic and anti-ferromagnetic ordering between spins in the layers has been predicted at filling factor 2.

In this paper we report the first observation of hysteresis and domain formation in such a system, a behavior most familiar for conventional ferromagnetic materials. We have studied transport properties of a <311> grown double-layer two dimensional hole gas confined in two 100 Å wide GaAs quantum wells separated by a 30 Å thin AlAs barrier. All results presented here are measured on a Hall bar along the <233> direction, but similar results are obtained for Hall bars along the <011> direction. The 2DHG has a mobility of 11.1 (m^2/Vs) and a concentration of 1.8 10^{15} (m^{-2}) equally distributed between the wells.

The thin barrier in our structure gives rise to very strong interlayer interactions and, at the same time, in contrast to the situation in a double-layer *electron* gas, does not induce significant tunneling because of the high effective mass of holes. This particularly implies a much smaller splitting between the energies of the symmetric and anti-symmetric subbands in the 2DHG.

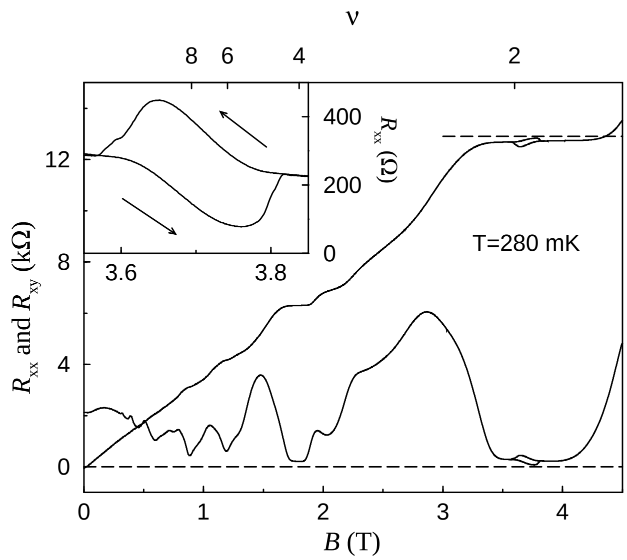

FIG. 1. Hall and longitudinal resistances of an ungated sample at a temperature of 280 mK, showing poor quantization in Hall resistance and considerable conductivity in the gap at filling factor 2. The inset shows more pronounced the hysteresis in the longitudinal resistance near ν=2. Arrows indicate the direction of the magnetic field sweep.

Figure 1 plots longitudinal and Hall resistances of our 2DHG versus magnetic field at a temperature of 280 mK [3]. The most striking feature in this figure is the pronounced hysteresis in both R_{xx}(B) and R_{xy}(B) traces near filling factor 2. When sweeping the magnetic up R_{xx} (R_{xy}) first decreases (increases), while on sweeping the magnetic field down R_{xx} (R_{xy}) first increases (decreases). The hysteresis is observed at low temperatures (T $<$ 0.6 K) in both AC and DC measurements, and its symmetry upon reversing the direction of the magnetic field is symmetric for R_{xx} and anti-symmetric for R_{xy}. The hysteresis is accompanied by a poorly quantized Hall resistance and a non-zero longitudinal resistance, unexpected for such a high mobility 2DHG. Remarkably, the hysteresis completely disappears and the quantization becomes exact when a thin metal film (gate) is placed on top of the 2DHG.

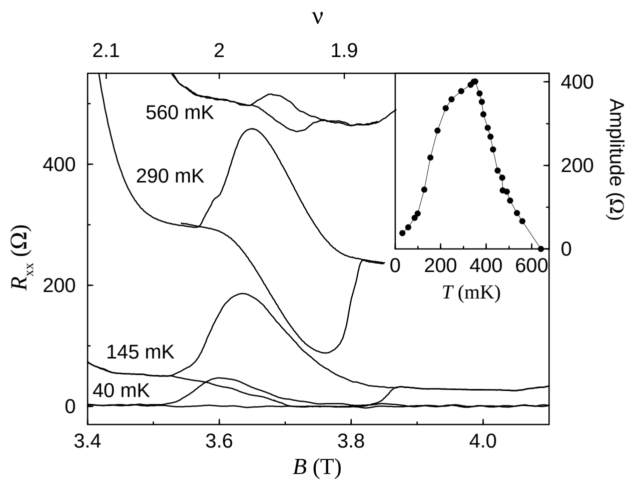

FIG. 2. Temperature dependence of the R_{xx}(B)-traces near ν=2. Inset plots the size of the hysteresis loop versus temperature.

Figure 2 displays the magnetic field dependence of R_{xx} near ν=2 for various temperatures. At high temperatures there is no hysteresis and R_{xx} around ν=2 decreases slightly with increasing magnetic field. Below about 0.6 K, the hysteresis appears. Initially the size of the hysteresis loop increases with decreasing temperature, until below 0.32 K the size decreases (see inset figure 2). A part of the decrease below 0.20 K is due to R_{xx} reaching zero on sweeping the magnetic field up.

The hysteretic feature is not stable, i.e. it slowly relaxes towards the middle of the hysteresis loop when the magnetic field is kept constant. Initially the time evolution of the signal is steeper than exponential, while for longer times it is much slower than exponential. At 0.50 K the lifetime of the hysteresis (defined as the time it takes to reach a resistance within 10 % of the value at equilibrium) is a few minutes, while at 40 mK the equilibrium cannot be reached within 3 hours (our longest experiment). The width and the size of the hysteresis loop depend slightly on sweep rate (the size decreases by 60 % on reducing the sweep rate by two orders of magnitude to 0.001 T/min), but this is solely due to the relaxation occurring during such slow sweeps and not due to the change of dB/dt.

Figure 3 compares temperature dependences of the longitudinal resistance of a gated and an ungated sample at total filling factor 2. For the gated structure, R_{xx} is thermally activated with an activation energy of 10.5 K in good agreement with the behavior of conventional quantum Hall effect (QHE) structures. Initially, the ungated sample follows the same activation curve, until below $\sim$2 K it starts to flatten. At even lower temperatures (T < 0.3 K) it is activated again, but with a much lower activation energy of only 0.56 K. During a temperature sweep, the measured R_{xx} corresponds to the middle of the hysteresis loop, i.e. it approximately falls on the line connecting the points at which the loop opens.

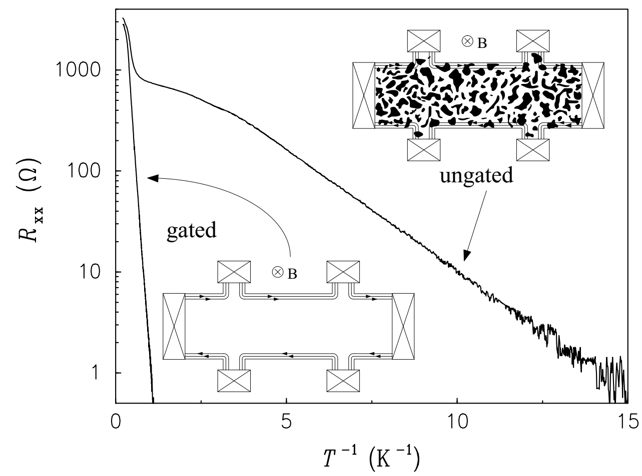

FIG. 3. Longitudinal resistance versus inverse temperature at filling factor 2 for the gated and the ungated sample. Activation energy for the gated sample is 10.5 K and for the ungated sample 0.56 K (below 0.30 K). While in gated samples at ν=2 edge channels propagate along the boundary of the sample, in ungated samples these edge channels are backscattered by the macroscopic density fluctuations (schematically indicated by the shaded regions).

Both the non-zero longitudinal resistance as well as the poorly quantized Hall resistance indicate the presence of significant fluctuations in the ungated 2DHG which give rise to backscattering and bulk conductivity [4]. Their absence in the presence of a nearby metal plate is presumably due to screening and implies the electrical nature of the fluctuations. To explain such fluctuations, we employ the theoretical prediction that strongly coupled double-layer quantum Hall systems at ν=2 exhibit transitions to an (anti-)ferromagnetic ground state and that away from this filling factor the ground state is destroyed [1,2](see figure 4). Then, at a magnetic field slightly away from ν=2, the energy gain due to the magnetic transition drives the system towards segregation into two macroscopic phases: the energetically favorable phase with ν=2 and the rest of the sample moved further away from this filling factor (see figure 3). The phases differ in their carrier concentrations in such a way as to keep the average value constant and the size of the domains depends on the energy gained in the magnetic transition and the energy lost due to stray electric fields. Since in gated samples the metal plate is 170 nm away from the top quantum well, the minimum size of the domains must be at least of this order of magnitude. At the lowest temperatures the longitudinal resistance in ungated samples is thermally activated again, which suggests the presence of a well defined gap separating the (anti)-ferromagnetic ground state responsible for the domain formation, from the Fermi energy.

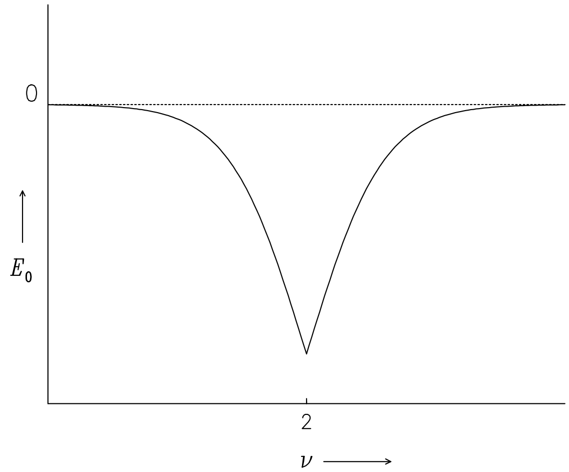

FIG. 4. Phenomenological model to explain domain formation in our ungated structures.

The above model also accounts for the behavior of the hysteresis which, as the experiment shows, is a non-equilibrium state of the system. The key-point is that the initial states just below and just above ν=2 are not identical. When approaching ν=2 from the low magnetic field side, the sample initially breaks up into domains with a *lower* density and the rest of the sample with a *higher* density. When approaching from the high field side, this is the other way around. In the former case, the topmost edge channel inside the domains can freely propagate through the rest of the sample, while in the latter case, this topmost edge channel is strongly reflected by the lower density inclusions as it is known to be the case in experiments with selectively gated QHE samples [4].

The slow relaxation of the hysteresis is likely to be due to changes in size and/or position of the domains so as to reach equilibrium. At the lowest temperatures the lifetime of the hysteresis becomes extremely long, either because the energy barrier for breaking up domains becomes larger than the thermal energy (as in ferromagnets) or because random potential fluctuations in the sample are larger than the thermal energy and pin the domains.

Finally, we want to mention that similar behavior has been observed at ν=4, although hysteresis appears at a much lower temperature (80 mK). At ν=4 the activation energy in gated samples is 3.7 K, while that in ungated samples is only 0.27 K.

In conclusion we presented experimental evidence for the formation of macroscopic domains in a strongly coupled 2DHG at total filling factor 2. The pronounced hysteresis observed in the longitudinal and Hall resistances near filling factor 2, is a non-equilibrium state, but one with an extremely long lifetime at low temperatures. A phenomenological model accounts for both the formation of these domains as well as the observed hysteresis.

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[3] Due to the very small splitting between the subbands, minima for odd integer filling factors larger than 1, are absent. See eg: R.J. Hyndman, T. Ihn, B.L. Gallagher, P.J. Rodgers, M. Henini, T.J. Foster and J.R. Middleton, Surf. Sci. **361/362** (1997), 117

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